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I. Experimental Design and Preliminary Experimental Data

Channing L. Ewing, Daniel J. Thomas, George W. Beeler, Jr., Lawrence M. Patrick, and David B. Gillis

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Joint Report

U. S. ARMY AEROMEDICAL RESEARCH LABORATORY

NAVAL AEROSPACE MEDICAL INSTITUTE

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Bureau of Medicine and Surgery
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U. S. Army Aeromedical Research Laboratory

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SUMMARY PAGE

THE PROBLEM

The purposes of the present investigation were fourfold:

1. To measure precisely the dynamic response or output of the head and neck to input acceleration.

2. To measure precisely that input acceleration.

3. To develop a method of obtaining the data in such a form that automatic data processing may be used.

4. To develop and validate a general method for the determination of the bioengineering characteristics of the human body with such precision, accuracy, and repeatability that a mathematical model of the human dynamic response to impact acceleration can be constructed.

FINDINGS

Preliminary results have provided qualitative information concerning the dynamic response of the head and neck from the photo data system used. Quantitative data are limited at this time because the complete electronic data train system has not yet been used. Uncorrected digitized data from an analog recording of transducer outputs of one sled trial are presented. Detailed analysis of dynamic response and other data is in progress.

ACKNOWLEDGMENTS

The success of the program was due in no small part to the assistance of many persons who are not listed as authors. CAPT Ralph H. Stowell, DC, USN, made the stainless steel bite-plates. CAPT Charles C. Pruitt, Jr., DC, USN, took impressions for the bite-plates and established the reference planes required to mount the transducers to the bite-plates. Mr. James L. Massey, Naval Air Rework Facility, gave valuable assistance in transducer mount and harness fabrication. Mr. Harlie Huffman, U. S. Army Aeromedical Research Unit, assisted by Specialist 5 Bobby Jo Collins, U. S. Army, and Specialist 4 James R. Newton, U. S. Army, built supporting electronics. Warrant Officer Daniel T. Hartfield, U. S. Navy, wrote the computer programs that implemented the data processing design of the experiment. Mrs. Elizabeth P. White, Naval Aerospace Medical Center, wrote the computer programs for plotting the data output. Dr. Margaret Smith gave valuable assistance in data reduction and analysis. The personnel of the Photographic Laboratory and of the Mathematical Services Laboratory of the Air Proving Ground Center, Eglin Air Force Base, aided the investigators immeasurably by providing all film processing and photographic data reduction.

ADMINISTRATIVE INFORMATION

Trade names of materials or products of commercial or nongovernment organizations are cited only where essential to precision in describing research procedures or evaluation of results. Their use does not constitute official endorsement or approval of the use of such commercial hardware or software.

INTRODUCTION

This paper describes the experimental design and preliminary results obtained in the study of $-G_x$ impact acceleration upon the head and neck of living human subjects. Dynamic response, as used in this investigation, is defined as both angular and linear accelerations of the head, and displacement of the head with reference to the point on the vertebral column where the input acceleration is measured, completely time phased.

Previous studies have demonstrated the difficulty of measuring accelerations and displacements of the head and neck as determined from a seat reference point (1,2). One difficulty has been in the means of generating the input acceleration. Many studies have been performed on acceleration facilities in which an initial acceleration was given the sled until it reached a certain velocity which then decayed gradually. A deceleration device at the distal end of the track subsequently produced the acceleration input pulse. A disadvantage of such a method of producing an input acceleration pulse was the necessity of establishing a condition of zero dynamic response prior to entry into the deceleration trap. If the head and neck were responding in any way to the initial acceleration pulse or subsequent velocity decay at the time of initiation of the input acceleration, the measured response to the deceleration pulse would be confounded to some degree.

Another difficulty lies in the complexity of the forces acting simultaneously on the head. A seated man who is restrained by pelvic and shoulder harness and subjected to a $-G_x$ acceleration has acceleration transmitted to his body by an interaction of his body with the seat back and restraint harness (2). The sled moves away from the pelvis in the direction of acceleration, but the pelvic restraint which couples the man to the seat transmits the acceleration to the pelvis and thus to the torso. The torso then attempts to rotate around the restrained pelvis in the mid-sagittal plane but is prevented from doing so by the shoulder restraint harness. Both the pelvic and shoulder harnesses stretch to their limit of elasticity for the input force. A reversal of torso trajectory then occurs, resulting in the torso being forced down and back. Concurrently, the torso is being moved through space with the acceleration vehicle.

The head and neck also respond to the accelerations transmitted to it by the torso by describing an arc with the center of mass of the head and neck rotating through space about a center of rotation in the neck or neck-torso junction area. In addition, Schulman et al. (2) have shown that the neck is capable of considerable stretch. Therefore, displacements of the head as measured from a seat reference point are difficult to interpret per se due to the complexity of motion of the entire sled-torso-head system.

Accelerations have been measured on the head by Stapp (1) and by Schulman et al. (2). Accelerometers used by Stapp in some of his earlier experiments were discontinued after a few runs because of "angular motion of the head and instability of the helmet on the head" (1).

Relative motions or differential displacements between the head and the torso, as well as the linear and angular accelerations acting on the head, must be determined in order to develop and validate either analog or mathematical representations of the human being. Furthermore, and most importantly, the differential motion and accelerations must be indexed to a completely defined input acceleration.

Tolerance limits have been determined for a range of values of certain independent variables of input impact acceleration; however, these input values usually have been measured only on the impact device. The interaction of the human body, restraint system, and chair during acceleration precludes accurate calculation of input acceleration to the body or any of its parts.

There is no intention in the continuing investigation reported here to determine tolerance limits. All trials are within the tolerance limits previously established by the pioneering work of Stapp and others.

EXPERIMENTAL DESIGN

In the design of this experiment, certain simplifying assumptions were made. The first was that all accelerations acting on the head and neck of the seated pelvic- and torso-restrained individual subjected to a $-G_x$ acceleration would be detectable at the first thoracic vertebra (T_1). The basis for this assumption is that under the stated conditions, all accelerations acting on the head and neck must be transmitted through the vertebral column. Only those additional accelerations transmitted by the soft tissues of the neck could be a source of error. Therefore, the accelerations measured at T_1 serve as input information to the head and neck.

The second assumption was that the head is a rigid body and the third, that all significant head and neck motion would be coplanar with the plane of induced acceleration, that is, the mid-sagittal plane.

In order to describe clearly the complex motion noted previously, all motion was considered as occurring in four two-dimensional coordinate systems: the laboratory, the sled, the spine-T_1, and the head.

The laboratory coordinate system can be any coordinate system fixed in the laboratory throughout the experiment. For convenience, it was selected as the position occupied by the sled coordinate system immediately prior to the onset of acceleration to the sled.

The sled coordinate system was selected as an arbitrary visual system fixed to the chair back with a known orientation to gravity.

The T_1 coordinate system was established visually as a two-point target system etched onto the T_1 mount, and electronically as described under the section on Transducer System and as shown in Figures 1-3.

Figure 1

Transducer mount locations and harness, static.

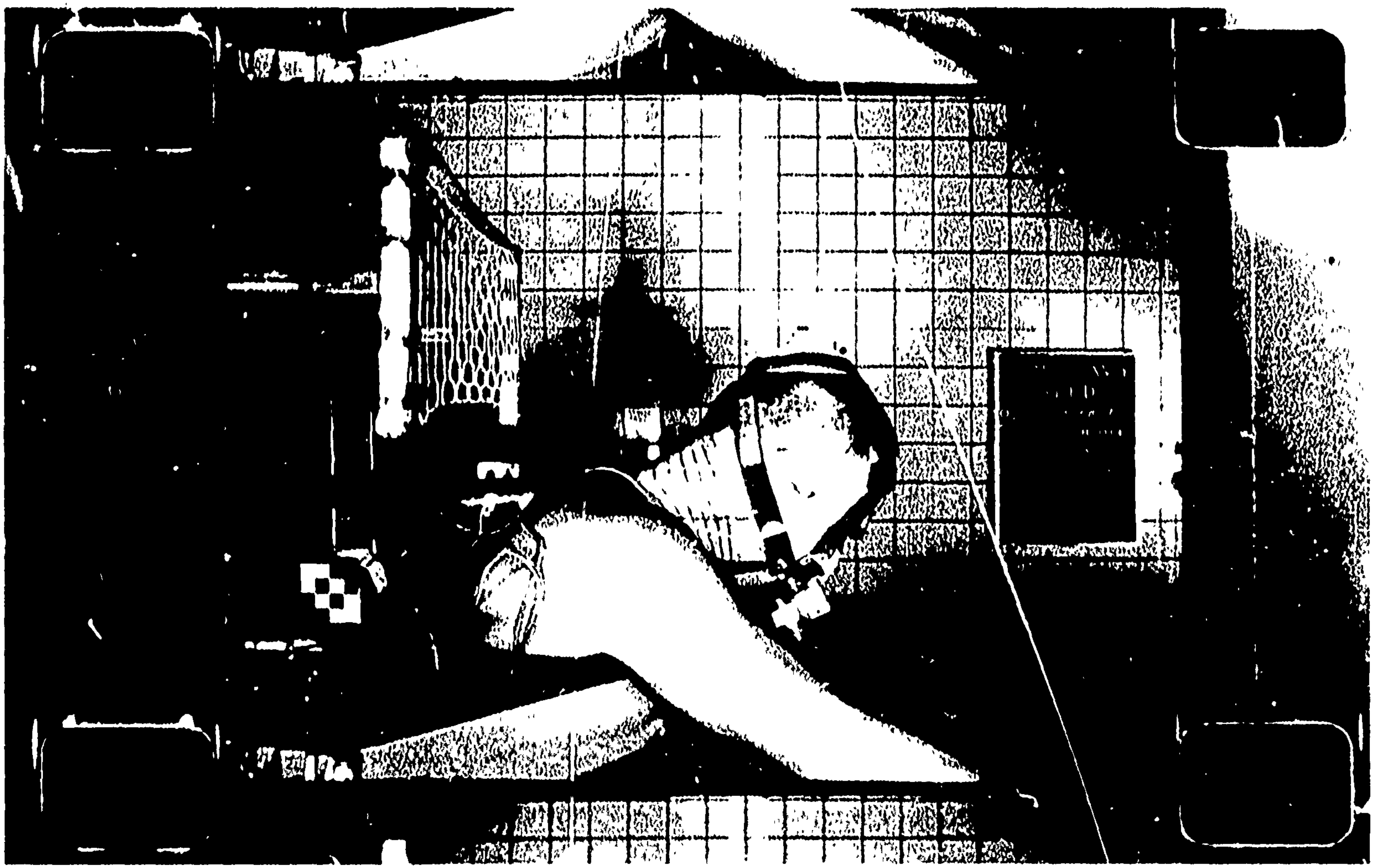
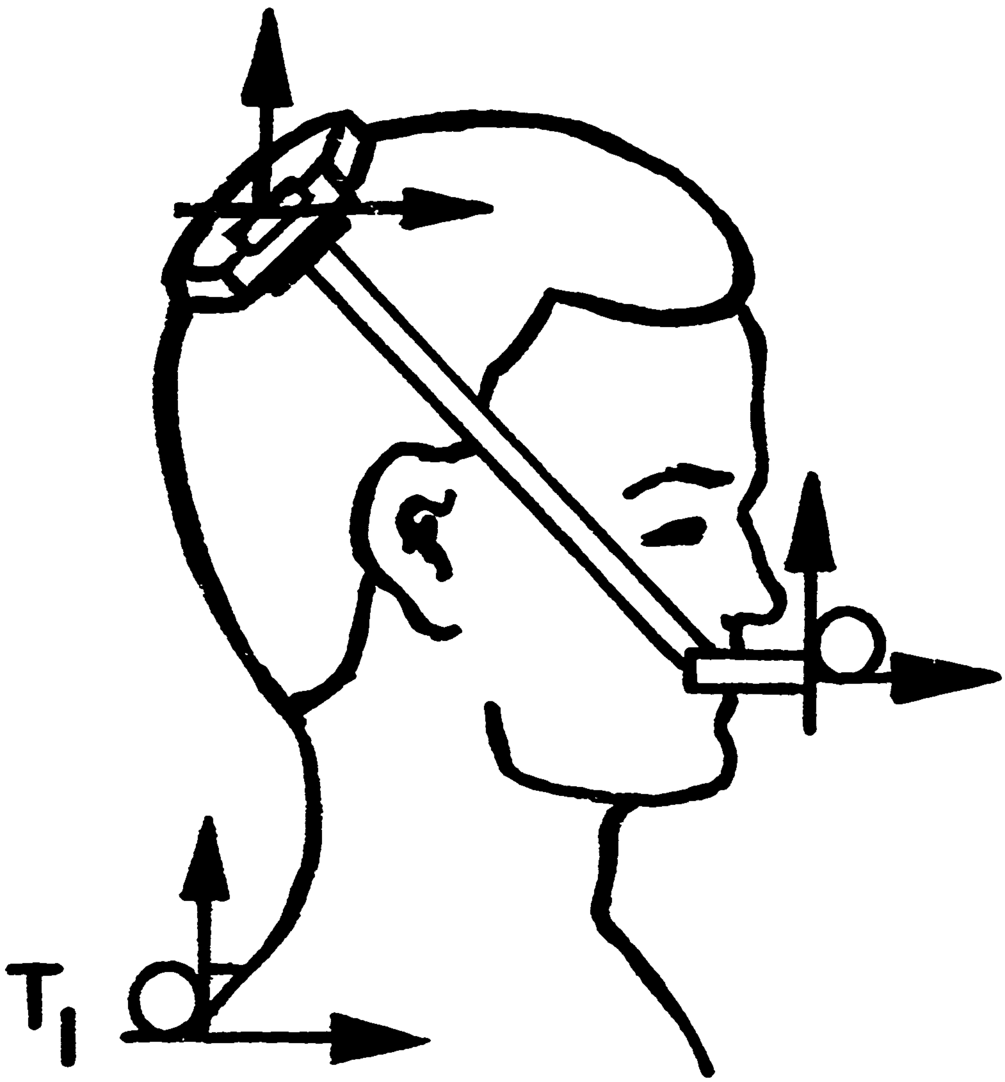


Figure 2

Transducer mounts and harness, dynamic. This frame was taken at time of maximum mouth-mount displacement relative to T_1 mount, run H014, 2.7 g (sled).



ACCELEROMETERS →

RATE GYROS ○

Figure 3

Transducer location and orientation, schematic diagram.

The head coordinate system was established visually as targets etched onto the head mount (which is molded to the bregma) and onto the mouth mount (which is rigidly attached to the teeth and hard palate), and electronically as described under the section on Transducer System and as shown also in Figures 1-3.

The output or dynamic response of the head is defined as the differential velocities, displacements, and accelerations of the head coordinate system with reference to the spine coordinate system.

Two redundant systems tracked the coordinate systems. In the first, high-speed high-precision photography was used to measure displacements of the coordinate systems. The velocities and subsequently the accelerations can be determined from the measured displacements by differentiation with respect to time.

The second system used inertial reference platform technology and established such a platform for each coordinate system of the head and spine. Each platform (coordinate system) had high-precision miniature transducers mounted on the subject's head and spine to measure the accelerations. The velocity and subsequently the displacement of the coordinate system could then be obtained by integration of the measured accelerations.

To obtain precise anatomical displacement information from the measured coordinate system displacements, several requirements must be met:

1. The transducers and the photographic targets must be uniquely fixed to each individual. This was satisfied by the construction of mouth, head, and spine mounts that can be placed only in one position on each man.

2. The position of each photographic target and each transducer must be determined and recorded for each individual. This was accomplished by X-ray and photographic anthropometry of each subject's head and neck with the mounts in place.

3. The position of each transducer and target in space must be determined just prior to the onset of acceleration. This was met by the lateral and posterior camera data and by the dc output of the accelerometers.

Once the numerical values of the anatomical displacements have been determined, a comparison can be performed to validate the results obtained by the use of either of the systems.

A "systems approach" was used for the entire experiment, and the equipment and techniques will be described system-by-system.

SYSTEMS DESIGN

PHOTOGRAPHIC DATA SYSTEM

High-precision, pin-registered, 16-mm movie cameras were selected to provide photographic data coverage. In the original experimental design, the camera was sled mounted, and the selected units operated perfectly during planned accelerations. The requirement that the cameras "ride" the sled arose from the desire to avoid the parallax problem common to all laboratory mounted (versus sled mounted) cameras, and was suggested by the work of Shulman and colleagues (2). Rates of 500 frames/sec were used in order to prevent possible loss of high-frequency response data.

One camera was mounted on the sled at shoulder level and to the right of the subject with the film plane paralleling the plane of expected motion, that is, with the camera pointed normal to the mid-sagittal plane of the subject.

A second identical sled-mounted camera was located directly to the rear of the subject and at shoulder level. The purpose of this camera was to determine rotations of the head and neck around the X and Z axes of the torso, as well as to determine motion of the T_1 mount with respect to the spine.

Each camera was fitted with a sled-mounted, high-precision, electrical camera timer which timed the center of shutter opening of each frame of film to within $\pm 100 \mu$ sec. The timers were reset to zero simultaneously with the production of the T_0 pulse (which is discussed under the section on Transducer System), thus producing positive time-locking of the cameras and the analog data on the tape recorder.

Photographic lighting during acceleration was provided by flood lights "riding" the sled.

Figure 2 is an example of the photographic information taken at the point of maximum differential head displacement during a 2.7-g (sled) run.

TRANSDUCER SYSTEM

Transducer systems were established at three locations.

The spine (T_1) system was positioned over the posterior spinous process of the first thoracic vertebra and consisted of two accelerometers mounted with their sensitive axes at right angles in the mid-sagittal plane, and a rate gyro with the sensitive axis perpendicular to the mid-sagittal plane of the subject.

The head system was positioned over the bregma (back of the head) of the subject and consisted of two accelerometers mounted with their sensitive axes at right angles to one another in the mid-sagittal plane.

The mouth system was positioned by a bite-block and consisted of a duplicate of the spine system.

The head and mouth system outputs were combined to form a single head output as described in the Data System section. The outputs of the head system and those of the spine system were used to track, each with respect to the laboratory coordinate system. The accelerations and displacements of the spine were then subtracted from those of the head to produce differential head-output data relative to the spine system input.

The transducers selected consisted of force-balance accelerometers and rate gyroscopes. The accelerometers weighed 0.5 ounce each, while the rate gyros weighed approximately 3 ounces.

The selection of transducers and the remainder of the electronic data train was made to limit the overall system error to 0.5 per cent. This criterion, plus the planned experimental program, dictated the choice of ±25-g linear accelerometers having a maximum error of 0.1 per cent full scale, and ±5000 deg/sec rate gyros with a maximum error of 0.5 per cent full scale within the range of expected angular rates.

Transducer outputs were hard wired to an Ampex FR1800L tape recorder at the accelerator site. Time-locking of the transducer recording with the photographic data system was accomplished by utilizing a square wave electrical pulse (T_0 pulse) to reset the camera timers to zero while recording the pulse on one of the tape channels.

The time axis of the experiment was established by the 100-kHz crystal oscillator in the tape recorder phase lock system. All transducer outputs recorded were phased to this time reference.

The tape recording was then played back by an identical recorder through an analog-to-digital converter, interfaced to a Univac 418 digital computer.

MOUNTING SYSTEM

Mounting of transducers on living human anatomy is a difficult procedure if valid information is to be collected. The following constraints were used in the development of the mounting systems:

1. Spurious motion of the transducer module must be held to a minimum.

2. The skin of the subject must not be broken.

3. The mounting platform must present no danger to the subject.

4. Rapid and easy donning and doffing must be allowed, and rapid changing of the transducer module from one anatomical module to another must be permitted.

5. Weight must be held to a minimum, yet strength must be sufficient to withstand expected accelerations.

It was determined that a mount consisting of three modules was required at each transducer system location on the head and spine. One module was required to obtain conformity to the subject's anatomy in a completely repeatable way; the second was required to maintain the transducers in a known standard configuration; and the third was required to mate the individual anatomical modules to the common transducer modules.

Three mounts were designed: The T_1 (spine) mount, the bregma (head) mount, and the mouth mount. The mouth mount and head mount were designed to compress the skull between them, thus preventing motion relative to the head during acceleration.

The T_1 anatomical module was constructed by making a pressure mold of the spinal column of the subject from C_5 through T_3 and cutting it to fit anatomically.

A pressure mold of the back of the shaven head of the subject was used to construct the head anatomical module.

The mouth anatomical module was constructed by making a metal casting of the upper jaw, and making provision for rigid attachment to the transducer module.

The connections between the head and mouth mounts were established and maintained under constant pressure by a harness. (See Figures 1 and 2.)

The T_1 mount was secured by a harness which maintained the mount on the selected site under considerable pressure. The acceleration pulse drove the mount against its spinal anchor point, thus improving stability during the dynamic event.

The three mounts were thus installed in a precisely repeatable location for each run. When the mounts were constructed for each subject, the transducer modules were installed on the center line so that each was coplanar with the other two. Once these relationships were established, changing the mounts from one subject to another was a short and easy task.

Immediately prior to each run, the subject was positioned so that all transducer systems were coplanar in the mid-sagittal plane (or plane of expected induced movement).

Motion of the mounts relative to the anatomical mounting site would produce spurious displacements and accelerations as measured both instrumentally and photographically. It was thus necessary to determine the presence or absence of such relative motion.

Motion of the T_1 mount relative to the spine was determined photographically by the posterior and lateral cameras. To date, no significant spurious motion has been detected.

Motion of the head mount relative to the mouth mount can be determined both instrumentally and photographically. The instantaneous relationship of the two mounts was derived mathematically from the analog recording. If the distance between them changed significantly, the resulting spurious data were noted.

The distance between the head and mouth mounts was measured photographically on the frame of film taken at the instant of greatest head acceleration. No change was detected within the limit of resolution of the photographic system, which is 0.25 cm. This was checked routinely in the photographic data reduction process.

DATA SYSTEM

The electronic data train used in these experiments was designed to minimize the manhours required to obtain the desired measurements and to improve their accuracy. Although high-speed photography is simple and useful for data collection, the analysis of the films requires an inordinate amount of time and does not lend itself to the determination of instantaneous accelerations.

The redundant transducer system was chosen to permit the instantaneous assessment of the differential relationships between the head and neck of the subject and permitted tracking the linear and angular components of the head and neck of the subject in inertial space.

The electronic data train used to record and compute the outputs of the transducers is diagrammed in Figure 4. The greatest source of error in the system was contributed by the analog magnetic tape recorder. A state-of-the-art recorder having an overall signal-to-noise ratio of 53 dB, or about 0.5 per cent root mean square noise, was selected. The remainder of the data train was chosen to reduce all other noise and inaccuracy to an insignificant level. The recorder was calibrated at the time of each experimental run in order to achieve the full benefits of the recorder specifications.

Signals leaving the transducers were amplified and scaled by integrated circuit operational amplifiers. These units were designed to permit the experimenter to expand the range of the transducer outputs so that the expected range of experimental output corresponded roughly to full range on the tape recorder. The setting was done with switchable resistor networks, and the stability of the amplifiers was such that monthly calibration was sufficient to guarantee a maximum error of 0.1 per cent.

The analog tape recorder used a phase-locked tape speed servo to provide short-term constancy and linearity, but the electronic stability was such that frequent recalibration was necessary. In addition, the machine used to reproduce the analog signals was also used by another experimenter in the Pensacola laboratories, so frequent calibration changes could occur. To minimize the time and effort required to retain system accuracy, a calibration sequence was built into the system immediately prior to each experimental run. This sequence recorded a series of constant voltage levels on each channel of the tape recorder. During subsequent data reduction, the output

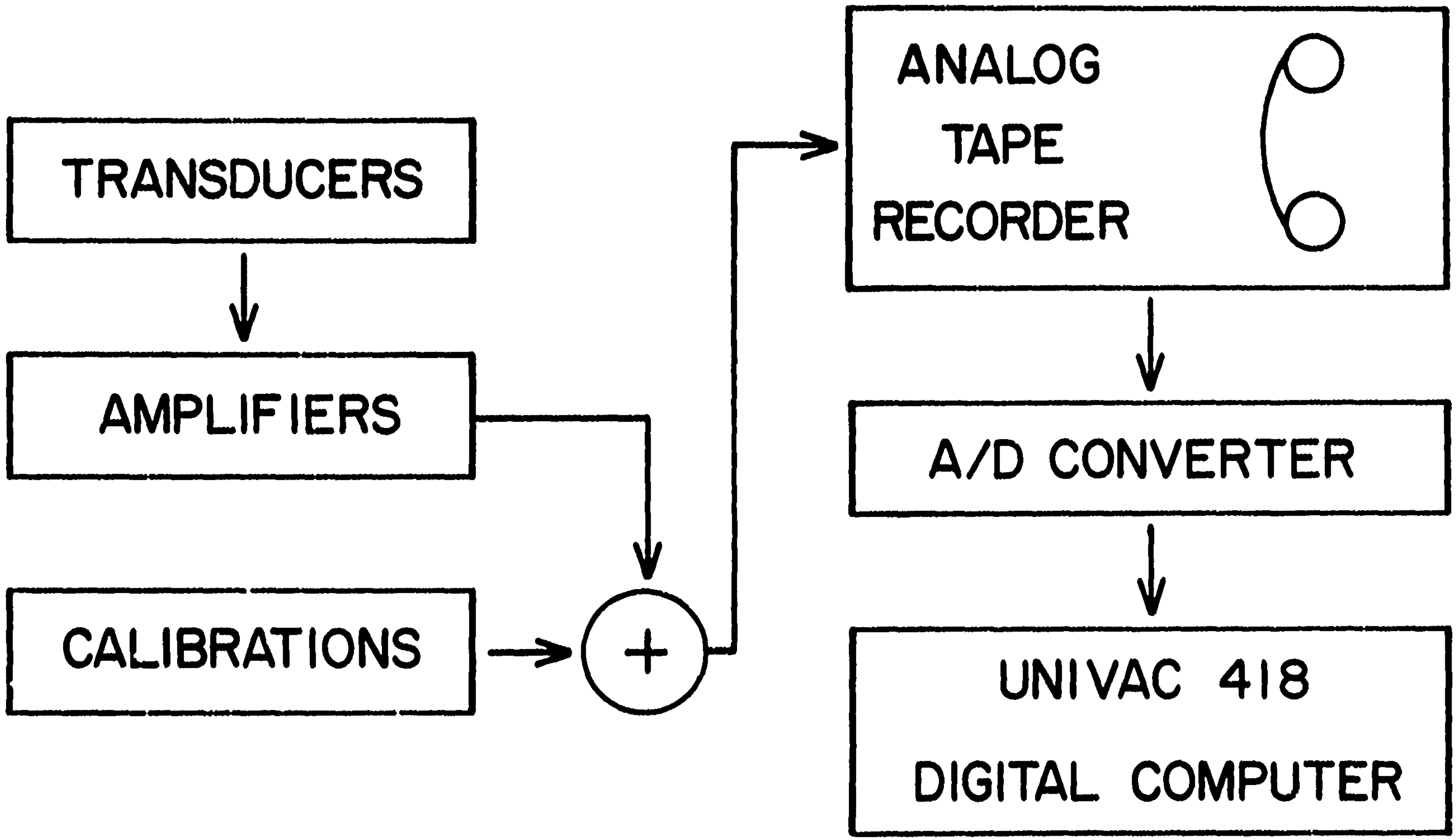


Figure 4

Data train schematic.

voltage levels of the calibration sequence were used to generate a first-order transformation to calibrate the incoming data.

The data were sampled at 2000 samples/sec with a 10-bit accuracy, and transmitted to the core of the Univac 418 for processing. The mounts shown in Figure 3 provided eight data channels which, along with a chair accelerometer track, were digitized in two passes over the tape, the passes being synchronized by the 100-kHz signal recorded for the recorder phase-lock servo. Once the data were resident in the computer, a series of processing programs was applied to them. The first program determined the calibration transformation mentioned earlier and combined it with punched card data from the transducer and amplifier calibration curves in order to convert the digitized data into units of cm/msec^2, and rad/msec.

In a second processing routine, data transcribed from a single photographic frame (still or motion picture) were used to determine the initial positions of the head and neck of the subject with respect to a gravitational coordinate system. Simultaneously, transducer data obtained immediately before impact were used to determine the initial position of the transducers in the system. The results from the initial-condition routine were retained for later use in processing.

The first data manipulation step involved transforming the two sets of head acceleration into a pair of accelerations parallel to the line joining the sets of transducers and a pair of accelerations perpendicular to this line. The accelerations were then averaged to produce a single pair of mutually perpendicular accelerations referenced to the mid-point of the line. This maneuver effectively eliminated angular accelerations from the tangential accelerations, and angular velocity (centripetal) effects from the radial accelerations.

Integrating the rate gyroscope outputs to obtain the angular orientations of the head and spine as a function of time was the next step. When the angles were obtained, the pair of accelerations representing the head and the pair representing the spine were transformed to obtain accelerations parallel and perpendicular to gravity. After subtracting 1 g from the vertical channels, the data were integrated twice to obtain the desired velocities and positions. As a final step, the spine positions were subtracted from those of the head to determine the differential measures.

All of the data were then available for plotting or use in further analysis. While there are currently no results available beyond the differential measures, it is anticipated that the data will be used in various modeling programs, and will be further analyzed as to frequency components, et cetera.

The description thus far has involved only the manipulation of the electronic data train. In order to validate these data and permit comparison, it was necessary to process the photographic data from the high-speed motion pictures.

The photographic data were digitized by recording the position of various target points on punched cards. The cards were then processed by the computer to obtain the same differential measures which were the final results from the transducer train. The photo data were further interpolated to correspond in time to the transducer samples. A plot comparison was then done. Although it was possible to compute velocities and accelerations from the photo data, numerical differentiation is inherently a noisy process, and it was felt that the ultimate position comparison was a more meaningful measure to use for validation.

ACCELERATOR SYSTEM

Precise determination of dynamic response with the instrumentation systems utilized require that the subject be initially at rest.

An acceleration device designed, constructed, and operated by Wayne State University Biomechanics Research Center was modified for use in this investigation by adding the numerous safety redundancies required for man-rating.

A sled was designed and constructed for this project, having a steel seat which permits forward and backward tilting in the mid-sagittal plane as well as rotation in the horizontal plane. A modified aircraft lap belt, shoulder straps with an inverted V, and a chest safety strap formed the restraint harness.

Seat back and shoulder harness heights were made adjustable to the individual, thus achieving maximum subject safety and restraint during acceleration and deceleration. This also permitted unhampered photography of the T_1 mount and the rear of the head and neck.

SAFETY

Safety system redundancies included:

1. Written countdown procedure.
2. Pressure checking at the firing console and at the accumulator, by separate persons.
3. Checking of reported pressures against scheduled pressures by a third party prior to firing.
4. Two key firing switches located at widely separated positions.
5. Warning horn.
6. Strict operating discipline.
7. Multiple abort switches located in widely spaced positions in the laboratory.
8. Dual hydraulic braking master cylinders activating one set of brake shoes on each side.
9. "Last chance" emergency braking system consisting of polystyrene foam logs.
10. Two-to-one safety factor dynamic proof testing of the entire sled system and all components prior to human runs.
11. Fail-safe subject-controlled abort switch.

APPLICATION

SUBJECT SELECTION

Volunteer subjects from the 28th Artillery Group, U.S. Army Air Defense Command, were initially screened carefully by medical history, examination of personnel and health records, and independent interviews with two flight surgeons.

The prospective subjects remaining after the screening were measured anthropometrically, and preliminary selection was based on the single criterion of sitting height. Volunteers were selected from the 5th, 95th, and 50th percentiles of the U. S. Navy Anthropometric Survey of 1964 (3), thus facilitating the use of subject sitting height as an independent variable in the experiment.

Candidates surviving the second selection were then examined thoroughly by specialists in aerospace medicine, dentistry, orthodontics, orthopedics, radiology, otorhinolaryngology, ophthalmology, neurology and psychiatry, and vestibular physiology. All candidates qualified in these examinations became subjects in the study, but only 5 of the original 30 volunteers successfully completed the entire selection process.

Two flight surgeons of the research team, who were physically qualified by the same standards, volunteered for duty and made experimental runs as subjects at each acceleration level.

Prior to a run, each subject was given a physical examination and a urinalysis and a careful interim medical history was obtained.

Following each run, the subject was carefully examined and studies made of his vestibular function, cardiac and neurological status, and urine. A 24-hour post-run history was taken prior to his next run.

PRELIMINARY RESULTS

A short program of "debugging" runs with living human subjects permitted evaluation of various types of photographic targets and their sites. It was found that the painted skin on the head was much too elastic to permit accurate measurement of head displacement, and that targets pasted on the skin interfered with skin dynamic response even at the low accelerations of those runs.

Qualitative information concerning the dynamic response of the head and neck was obtained from the photo data system on those runs. The head and neck translated linearly rearward almost as a unit until a limit was reached. The head then began a rotation about a center where the head and neck joined, while the neck itself rotated downward. The neck reached its maximum rotation from the vertical at approximately the time that displacement of the head from the T_1 mount reached a maximum value.

Quantitative data from those runs are limited due to the incomplete state of computer program "debugging." At this time the complete data train has not been used, although programming has been completed. However, preliminary analysis has yielded some quantitative data.

Uncorrected analog outputs from transducers mounted only on the spine and at the mouth are presented in Figure 5 for run H015 to demonstrate the time phasing of the human-mounted transducer outputs relative to the sled accelerometer outputs and to each other.

On that run, the input variables included rate of onset of sled acceleration of 140 g/sec, peak sled acceleration of 2.8 g, and duration of sled acceleration pulse of 440 milliseconds. The subject's sitting height was 36.2 inches, or 50th percentile, according to the Navy study (3).

Uncorrected digitized data from the analog recording of transducer outputs of that run are presented in Table I.

The final analysis will be of much greater detail and in a different format.

Data obtained from photographic analysis are demonstrated in Figure 6 for a 2.7-g (sled) peak. While only two output variables are given in that figure, the final analysis will include nine. The data will also be analyzed for five independent input variables.

No comparisons are presented in this report but are being performed.

Table I

Time Relationships and Magnitudes of Parameters of Run H015

	Time after Onset of Acceleration, (Milliseconds)	Magnitude
Peak sled acceleration	20	2.8 g
Peak T_1 resultant acceleration	40	4.9 g
Peak head resultant acceleration	85	7.6 g
Peak T_1 angular rate	100	200 deg/sec
Peak head angular rate	105	550 deg/sec

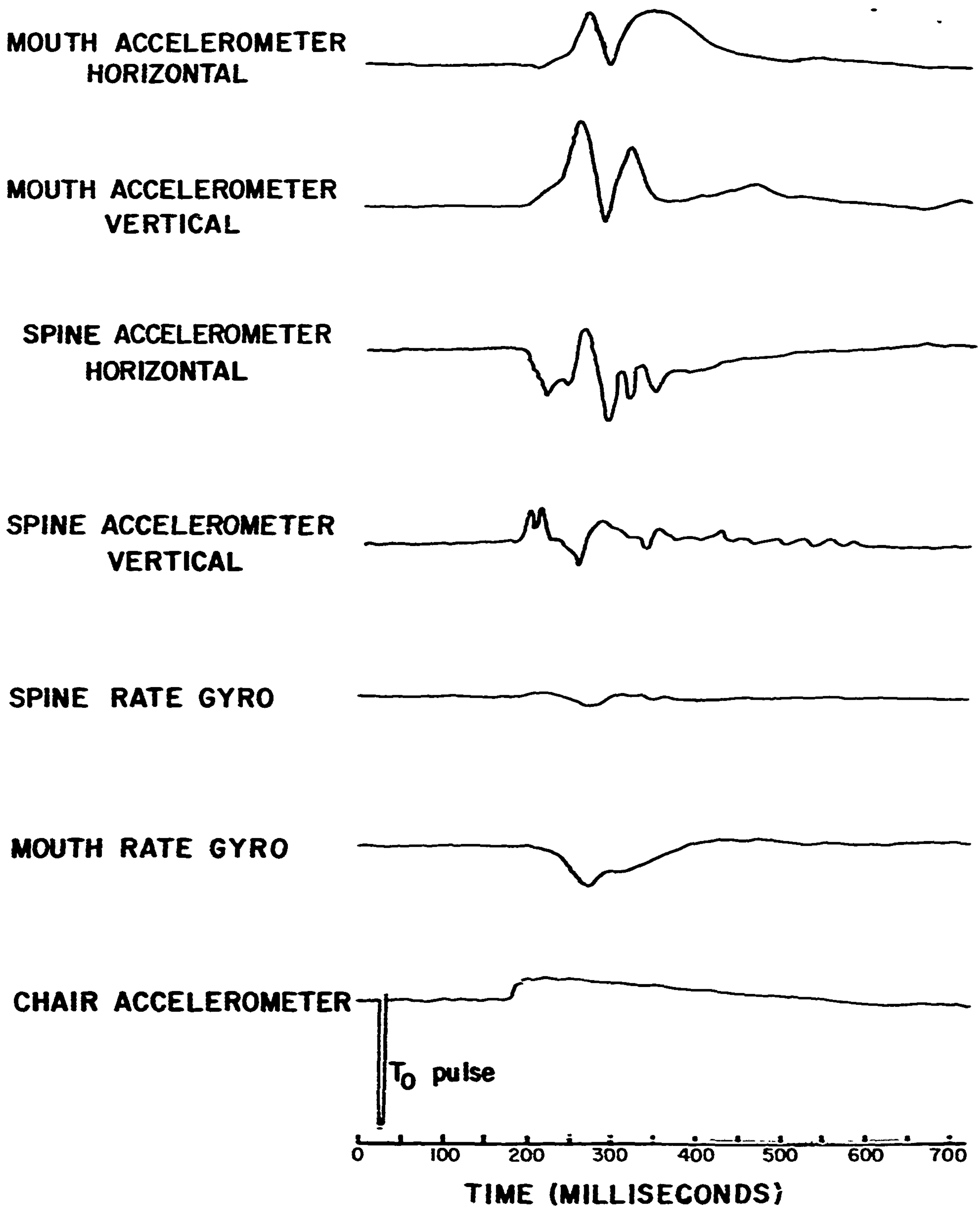


Figure 5

Time-phased mouth and spine measurements, derived from transducer system outputs, run H015, 2.7 g (sled).

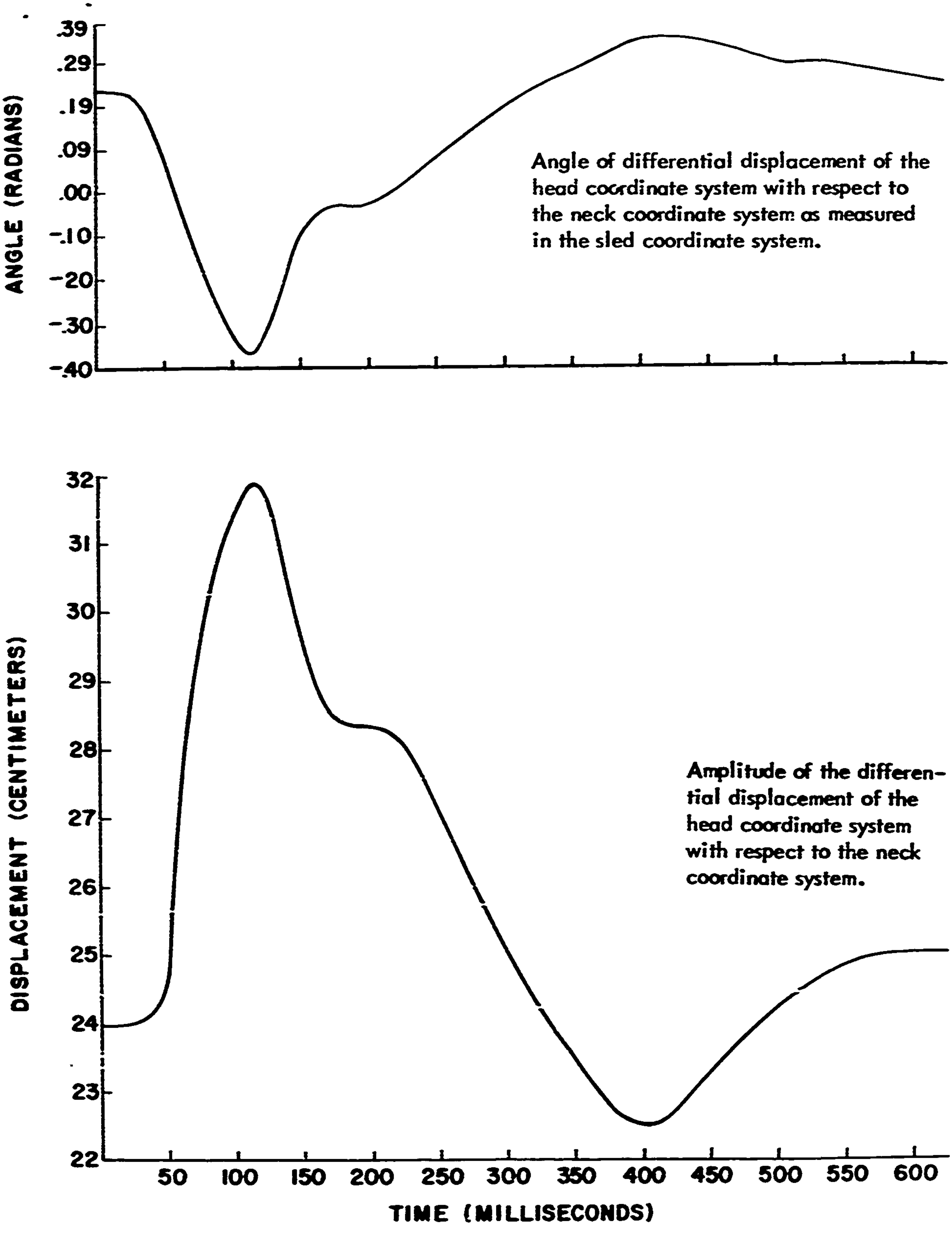


Figure 6

Time-phased head and spine transducer system outputs, run H015, 2.7 g (sled).

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13. ABSTRACT

Under the direction of the principal author, a joint Army-Navy research study, in cooperation with Wayne State University, is underway to determine the dynamic response of the head and neck of living human subjects to $-G_x$ impact acceleration, using transducers to measure differential displacements and differential angular and linear accelerations of the head with reference to the base of the neck in response to the input acceleration measured at that point. A redundant photographic data system is being used for validation. Preliminary results are presented.

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differential displacements						
differential angular and linear acceleration						
biomechanics						
bioengineering						
impact acceleration						

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